Global Workspace Theory Inspired Architecture for Autonomous Structural Health Monitoring

31 July 12

A Framework for Incorporating Contextual Information to Improve Decision Making

Multifunctional Materials for Defense Workshop

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Overview

- An architecture is presented for a structural health monitoring (SHM) system using the framework of intelligent agents
  - Combines reflexive and deliberative elements
  - Includes information fusion, feedback, and context-based reasoning to achieve goals
- The architecture is demonstrated in the laboratory on a representative airframe component
- Benefits of the architecture are summarized

Outline

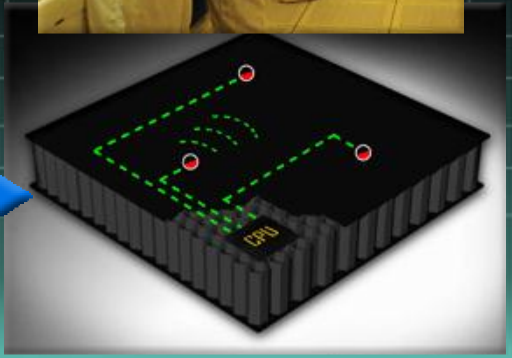
- Background
  - Integrated Systems Health Management (ISHM)
  - Structural Health Monitoring (SHM)
  - Intelligent Agents
- Agent Architecture for SHM
- Experiment and Results
- Summary

Integrated Systems Health Management

Any system that collects, processes and manages health data to assess the current condition of an aerospace vehicle and determine its ability to perform a given mission.

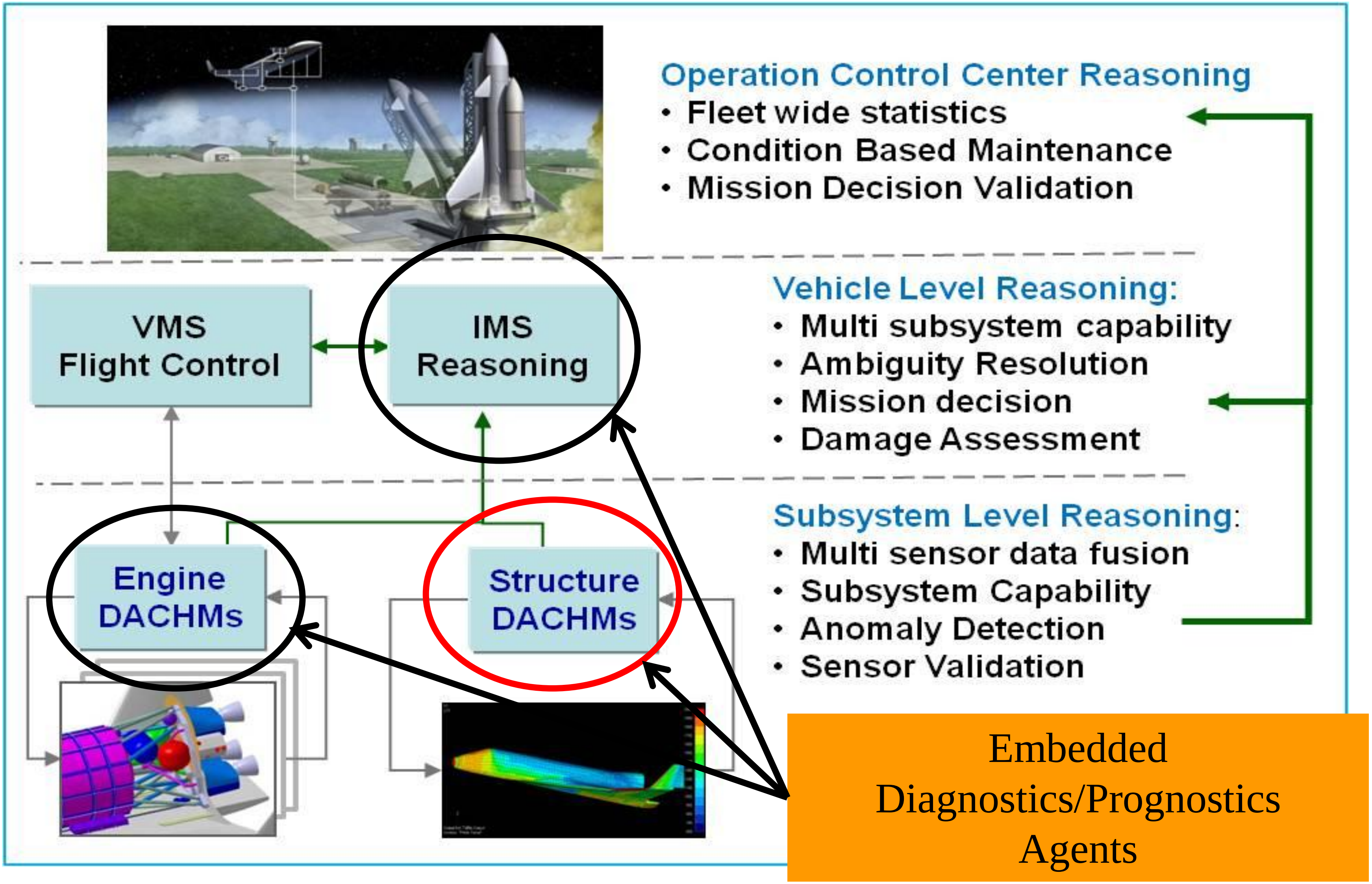
Determine Ability to Perform Mission

Assess Damage



Detect Damage

ISHM Architecture



Structural Health Monitoring

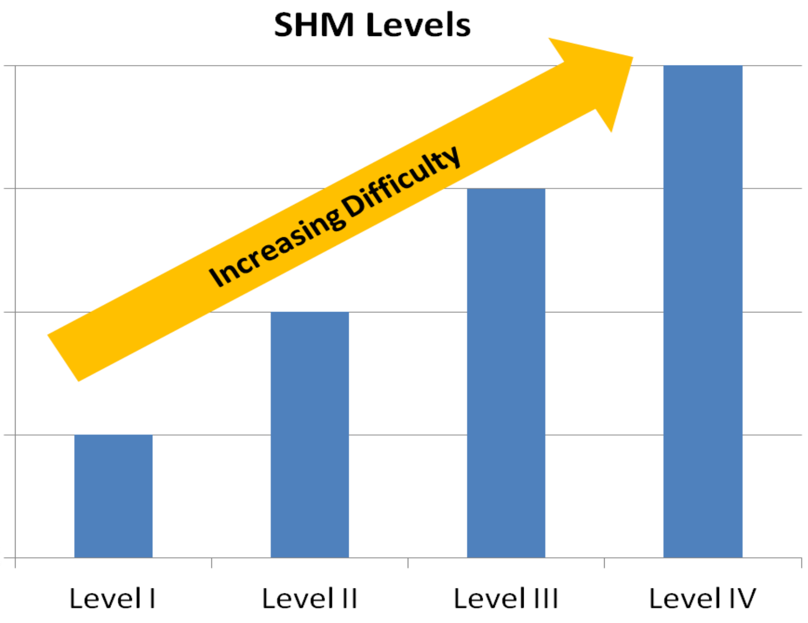
- SHM systems are automated methods for determining adverse changes in integrity of mechanical systems
- SHM systems are designed to answer the following:

What are consequences of damage?

How significant is the damage?

Where is the damage?

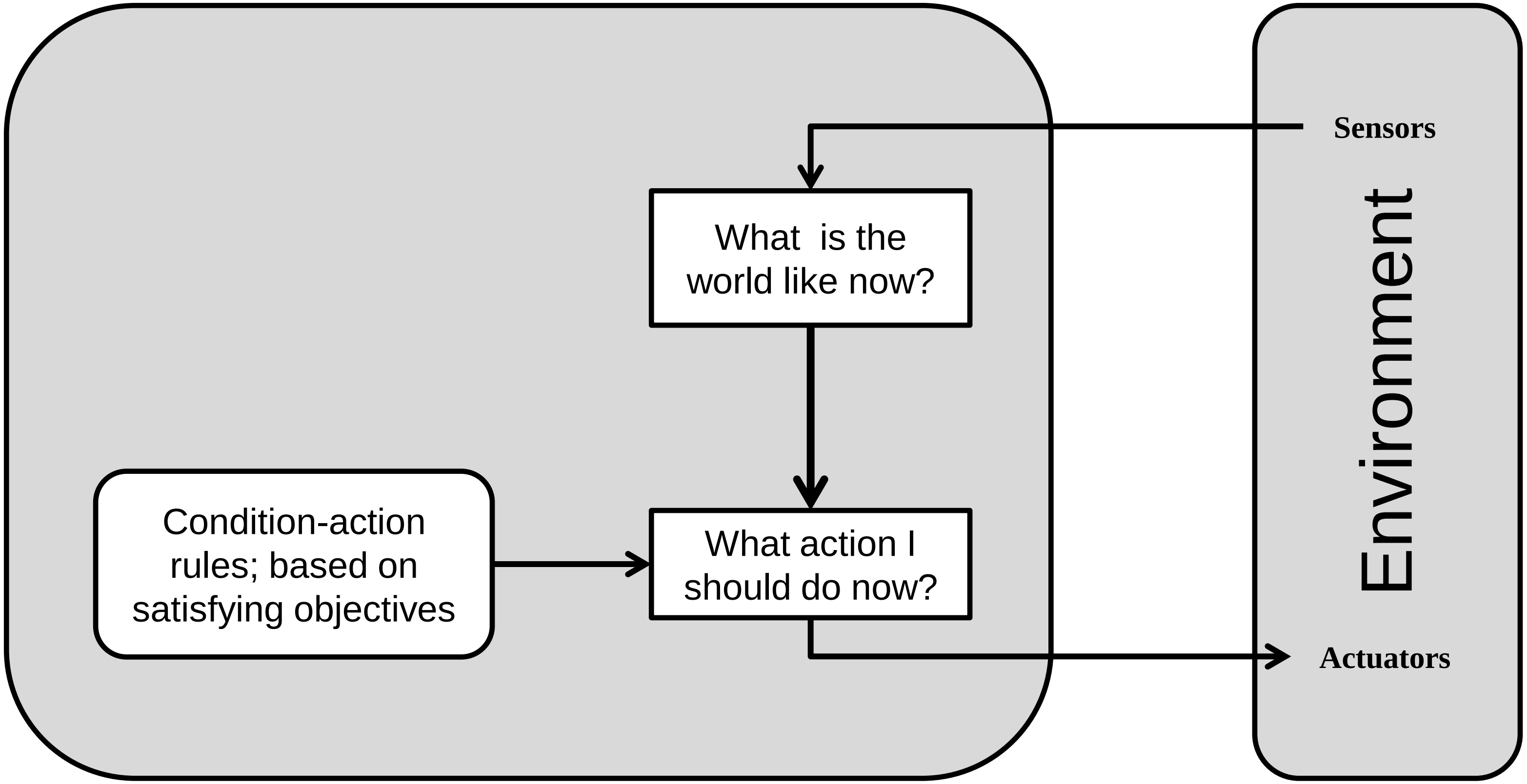
Is there damage?



- Mainly based on sensor data; damage estimates based on statistical pattern recognition methods

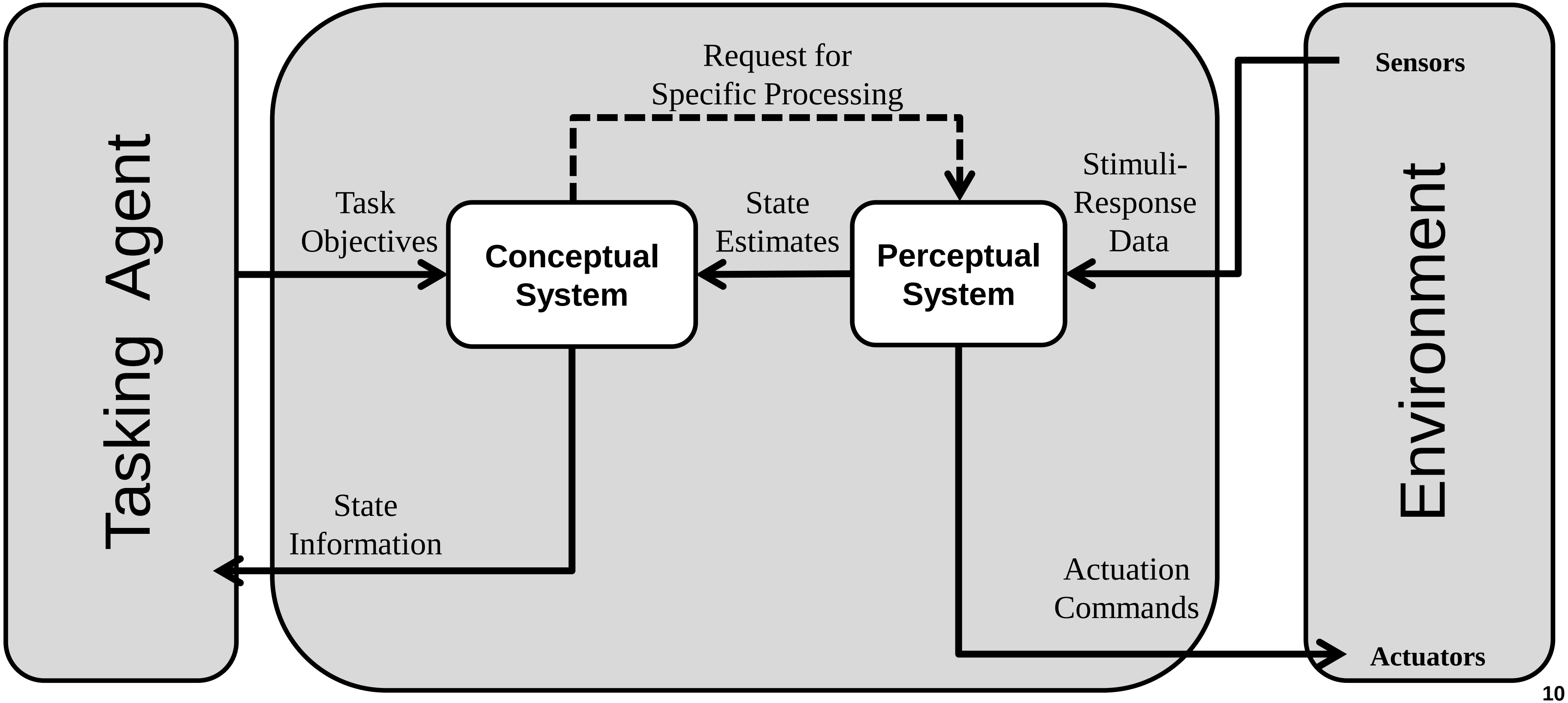
Simple Reflex Agent

An agent is a computer system, situated in an environment, capable of autonomously selecting actions, to best satisfy specified objectives

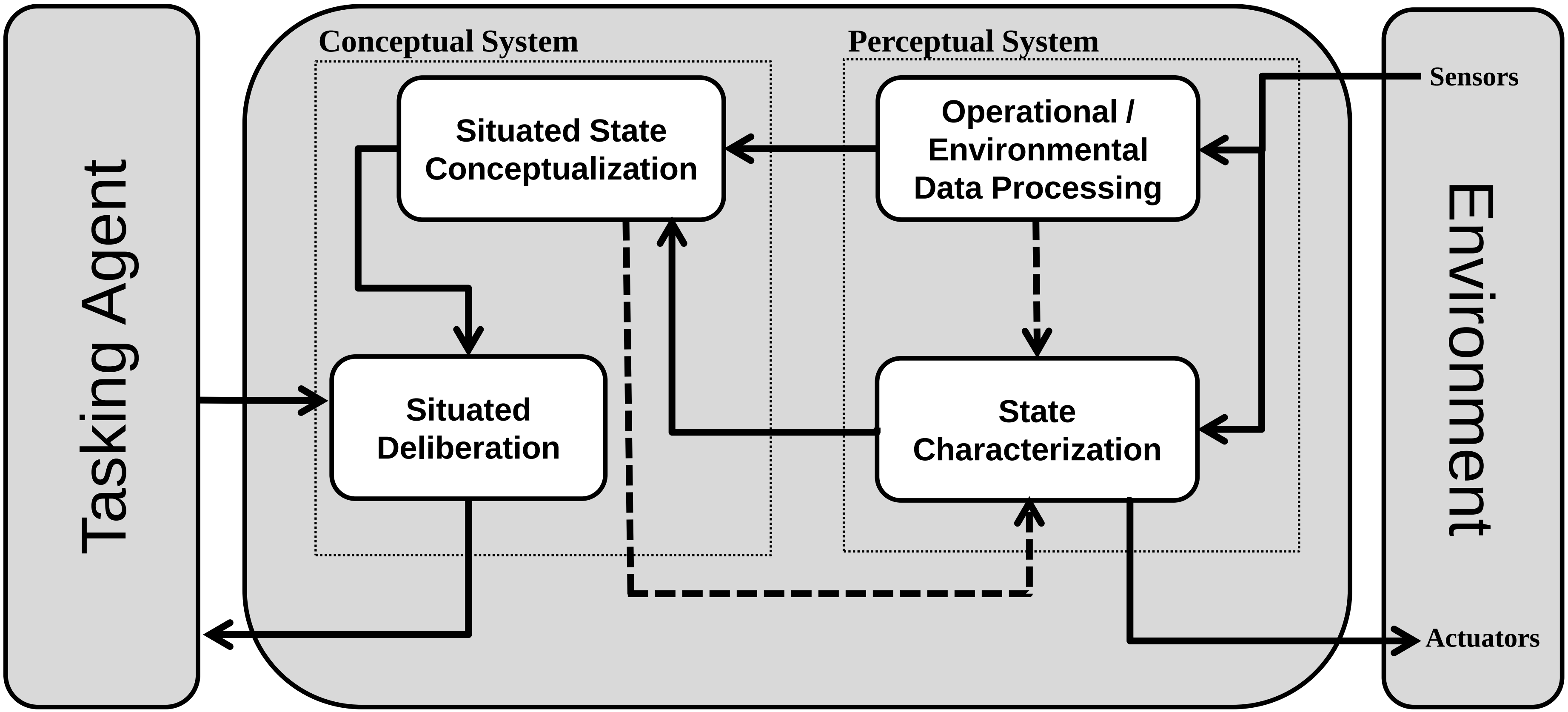


Intelligent Agent Architecture – Overview

- Intelligent agent architecture combines perceptual (sensory data) and conceptual (using context and objectives) processing to perform condition-dependent reasoning for state selection



Intelligent Agent Architecture – Detail



Perceptual and Conceptual Blocks

Perceptual

- Operational and Environmental Processing
  - Measurements that give context; indicate how the vehicle is being operated
- State Characterization
  - Estimate health status from sensor data

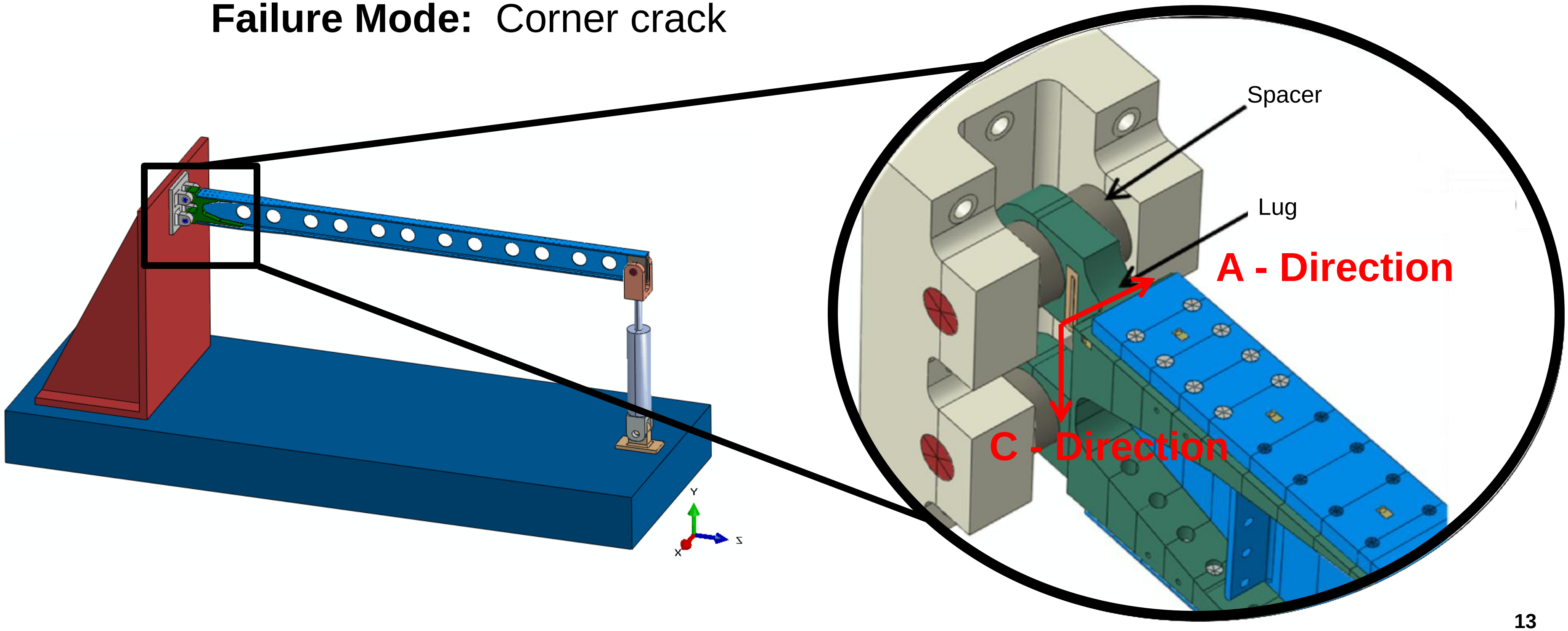
Conceptual

- Situated State Conceptualization
  - Use context information and/or physics-based models to refine state estimates; request additional measurements
- Situated Deliberation
  - Choose action to best satisfy objectives from the Tasking Agent given the current context and state estimates

Example SHM Application

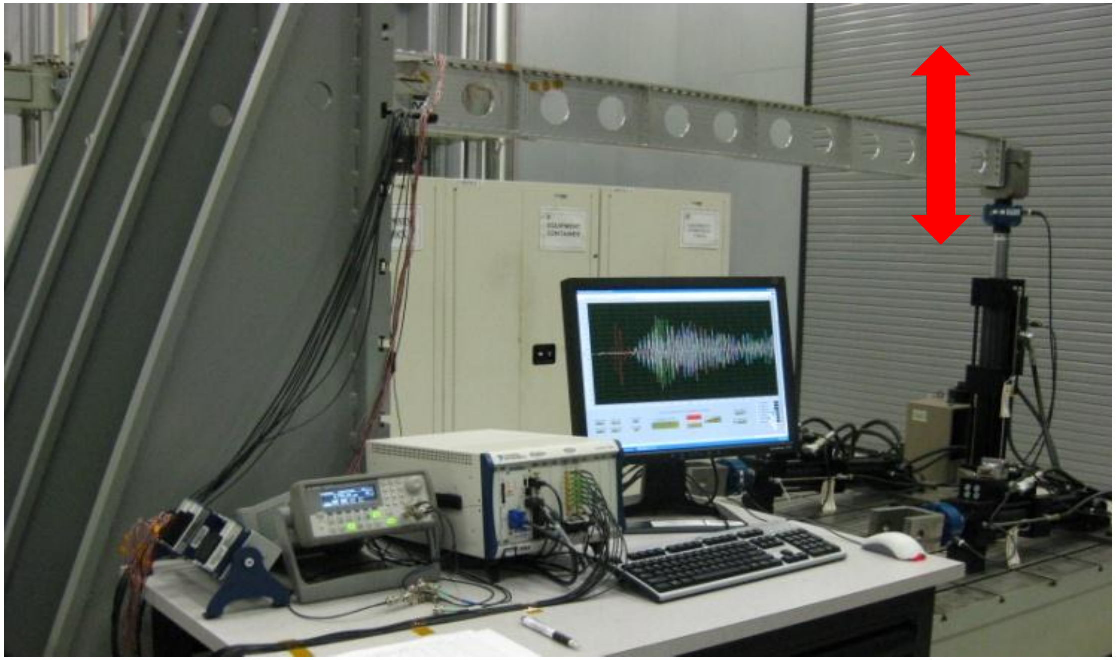
- Apply the framework to representative aircraft component
  - Low level information (estimated crack length) is mapped to provide high level information (risk)

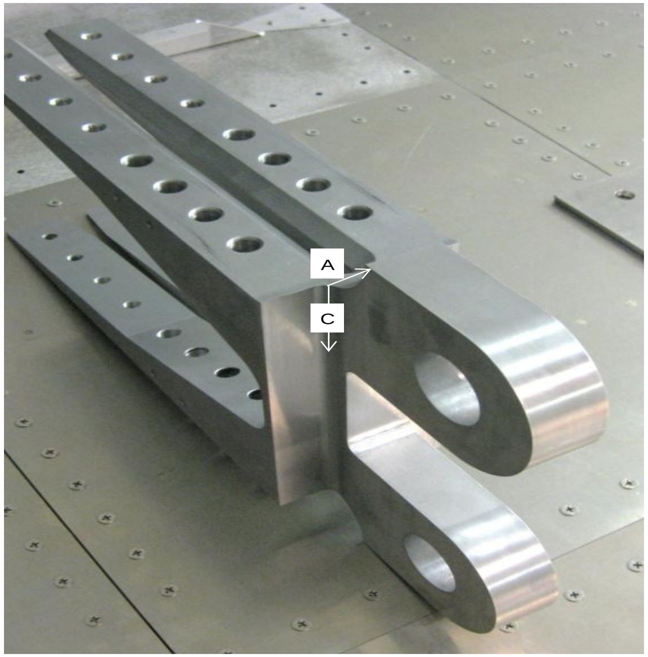
Flight Critical Component: Wing Attachment Lug
Material: 6061-T6 Aluminum Alloy
Failure Mode: Corner crack



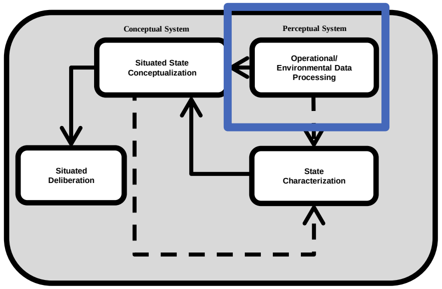
Wing Attachment Lug

- **Loading:** Constant amplitude sinusoid between 0 and 1000 lbs
- **Estimated Life:** 14,500 cycles
- **Estimated Critical Crack Size:** A = 0.35” and C = 0.70”
- **Run:** {1000 ,500, 250} cycles, pause, record signals and visual crack



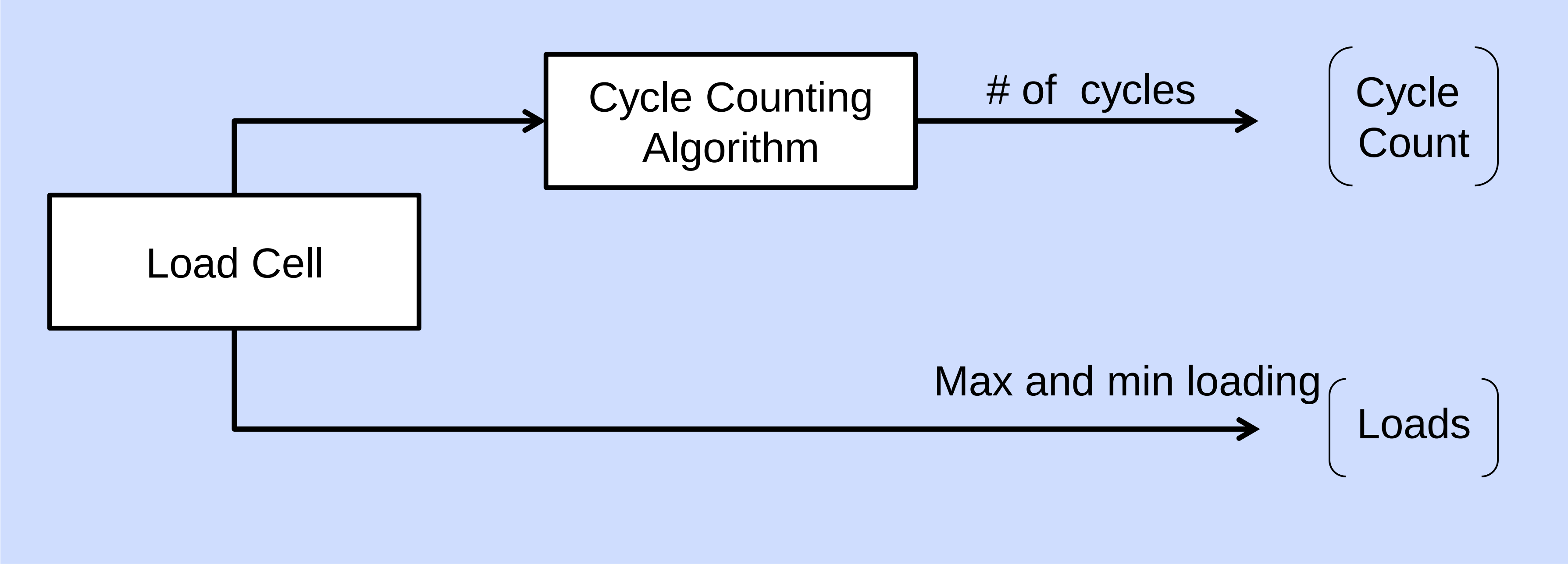


Operational and Environmental Data Processing



- Loads
- Cycle Count

Operational States



State Characterization

Actuators and Sensors

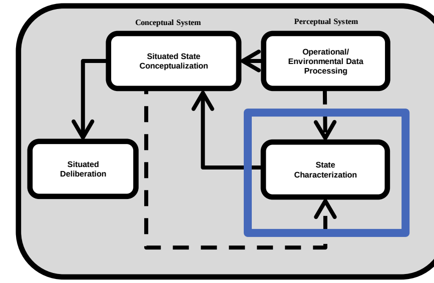
Piezoelectric elements

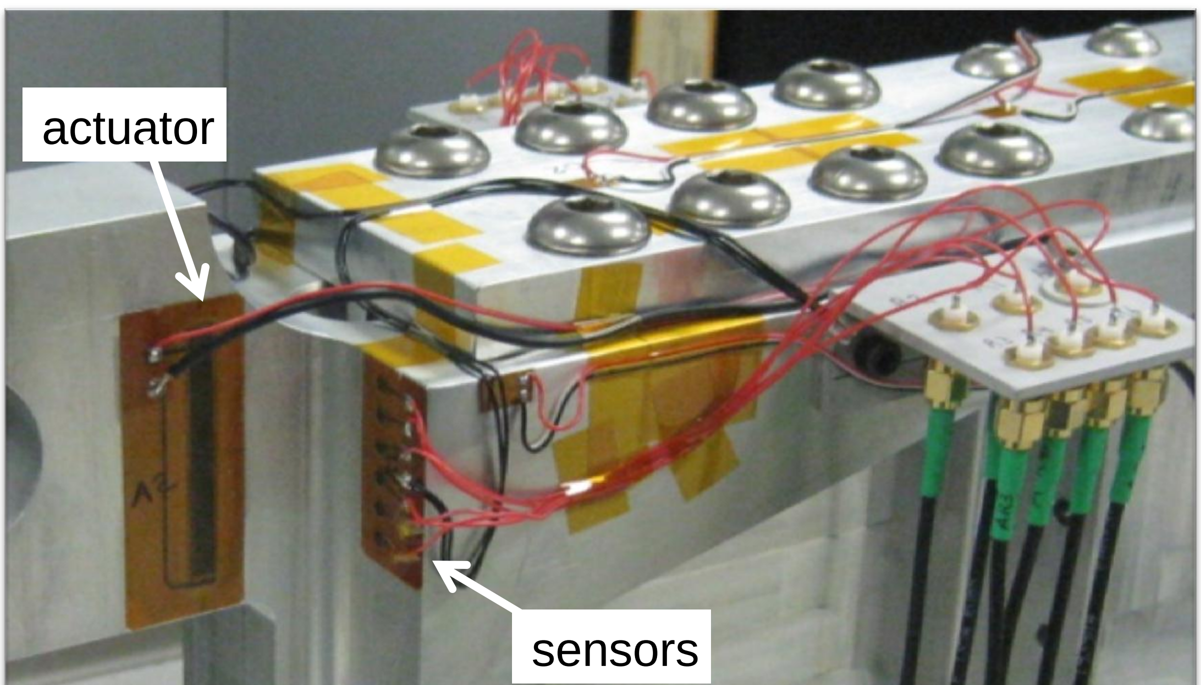
Sensing Modality

Ultrasonic elastic waves

Damage Detection and Estimation

Regression models and neural networks

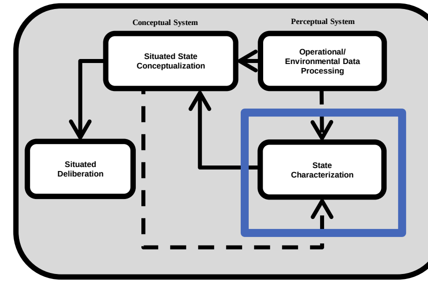


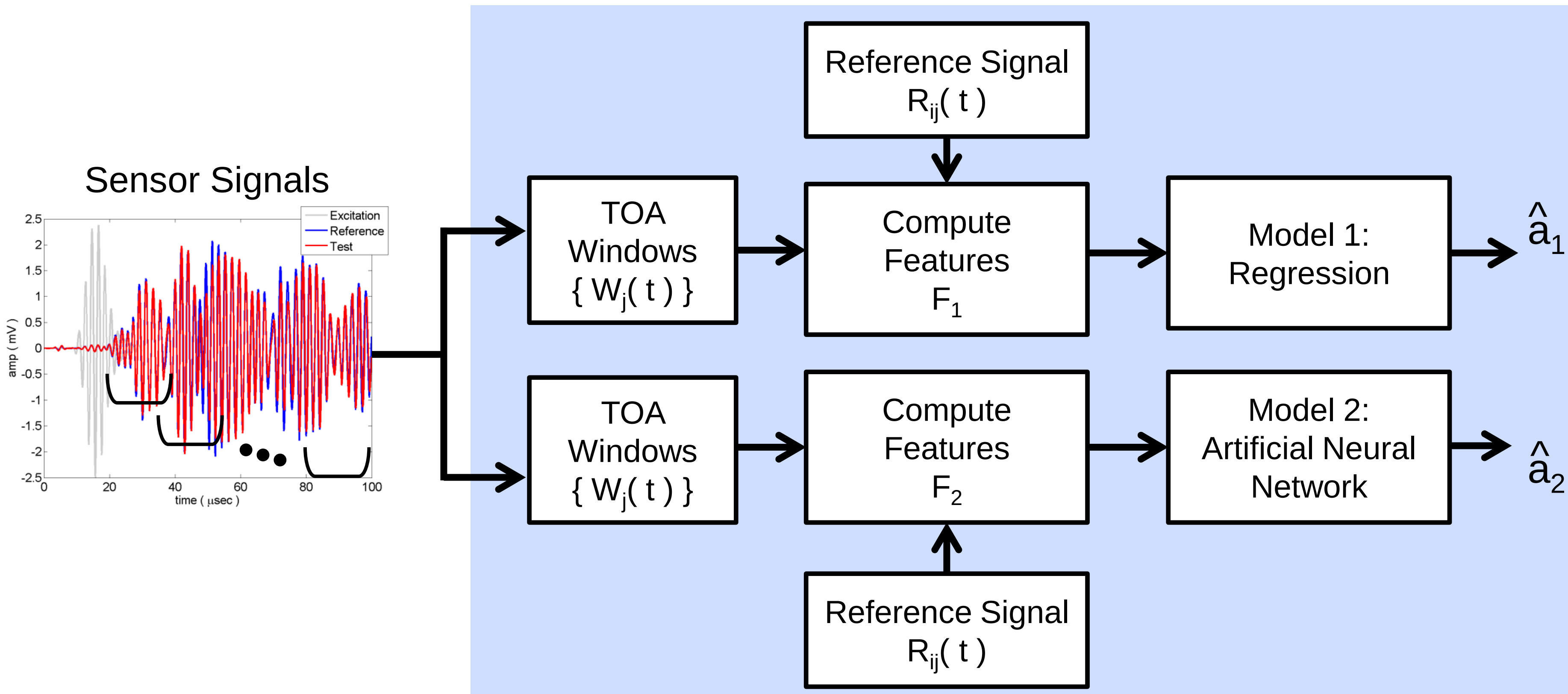


State Characterization

- Models trained to map changes in received sensor signals to estimated crack lengths

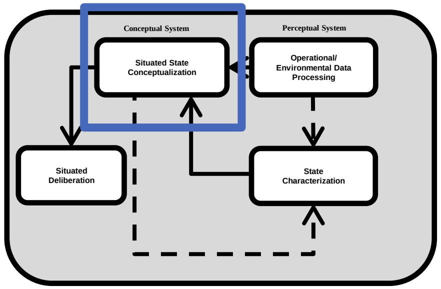
Damage State

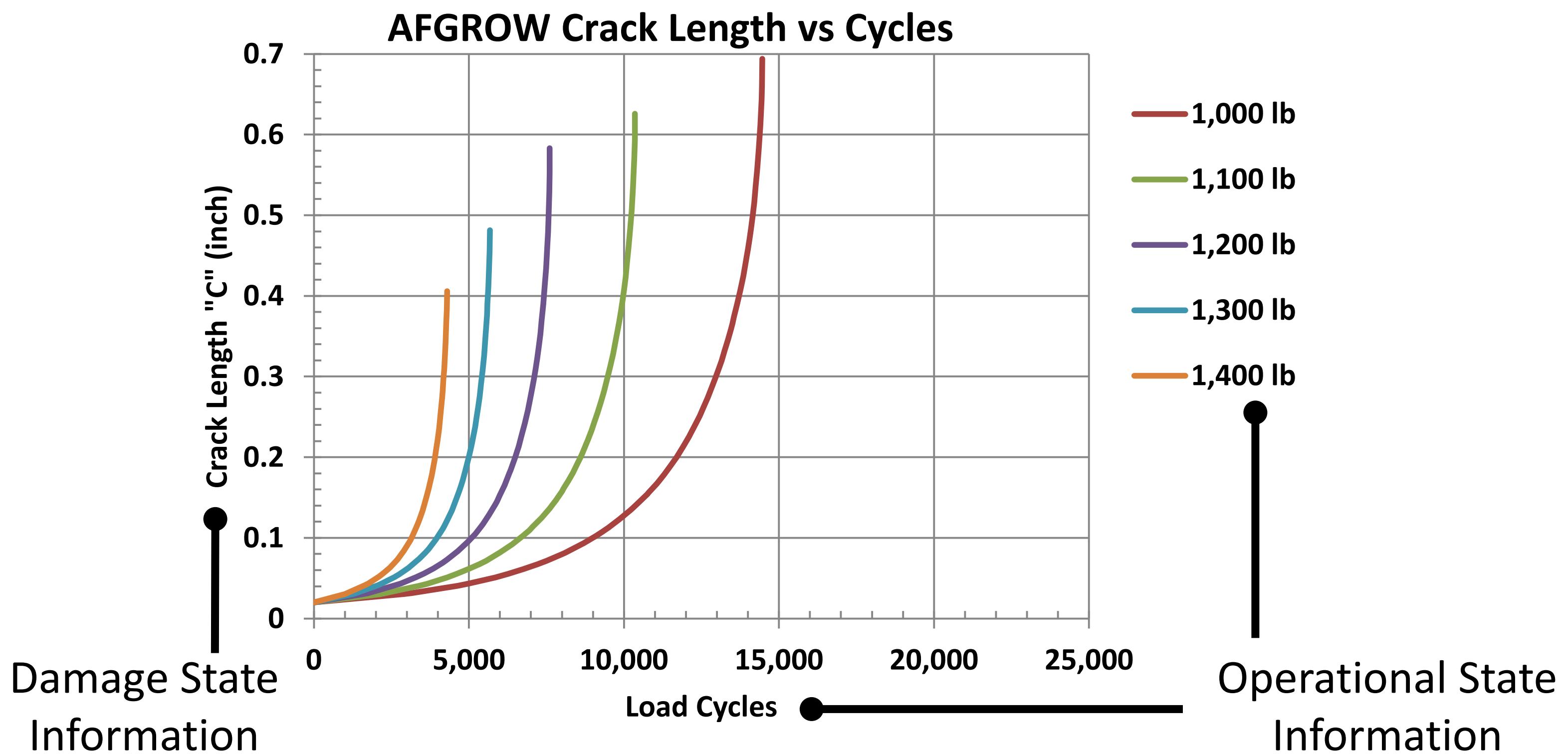




Situated State Conceptualization

- AFGROW is predictive software for crack growth
- Situated Conceptualization includes rules for
  - fusing state estimates with predicted growth
  - requesting additional measurements

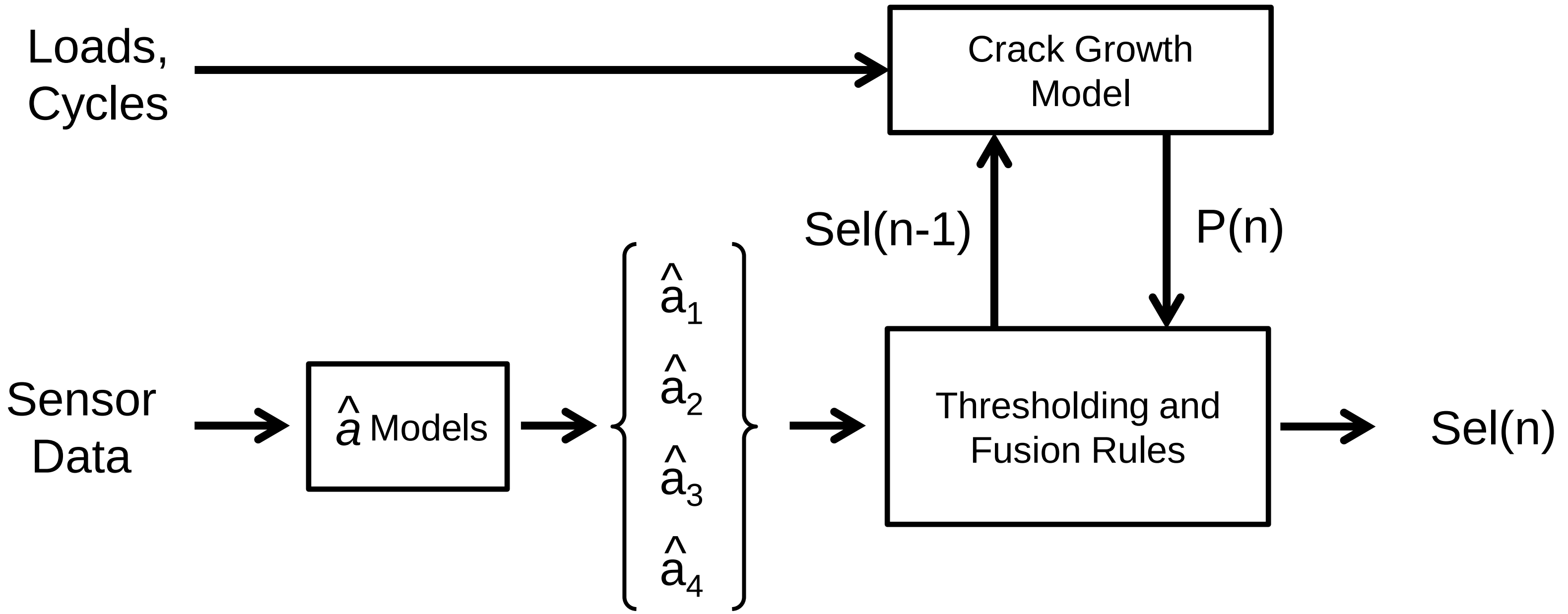




Assumed initial flaw size = 0.02”

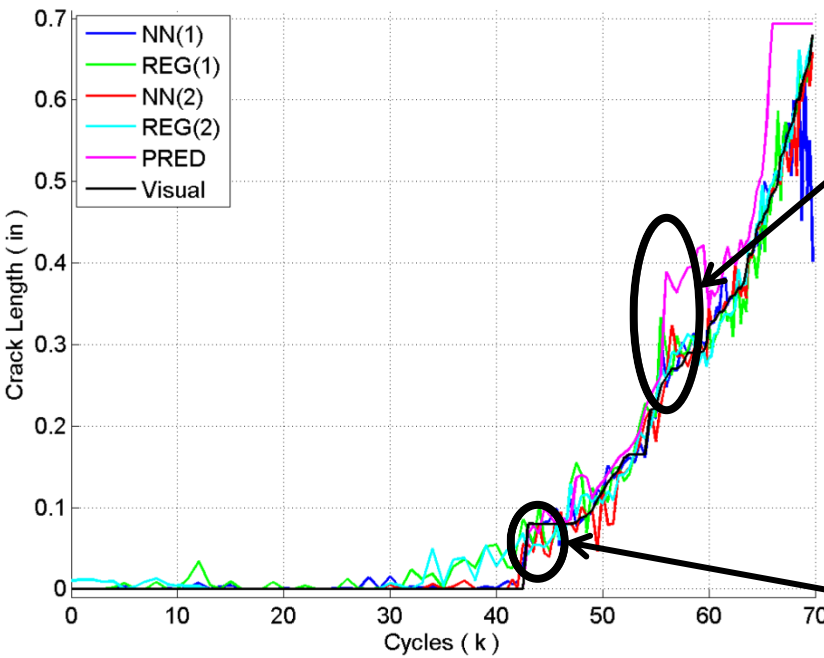
Situated State Conceptualization Scenario

- Assume 4 models available for crack length estimates
  - estimates 1 & 2 preferred over 3 & 4; simulates request for add'l data
  - threshold for declaring crack detection = 0.02"
- At each measurement cycle, apply crack growth model based on loads and elapsed cycles to produce predicted length, P(n)
- Selected crack length at cycle with agreement-based averaging of preferred estimates and P(n)



Situated State Conceptualization

Estimated and growth model agreements for averaging

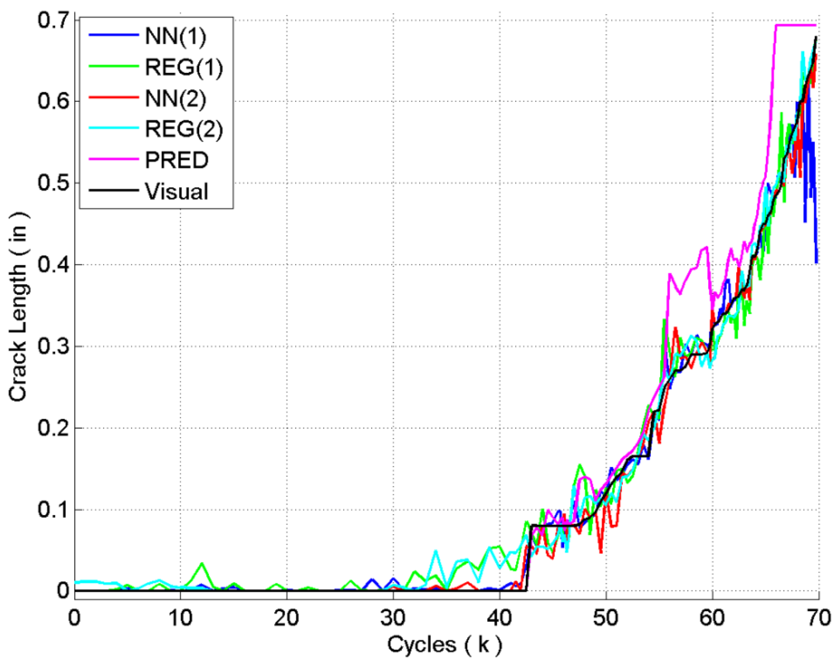


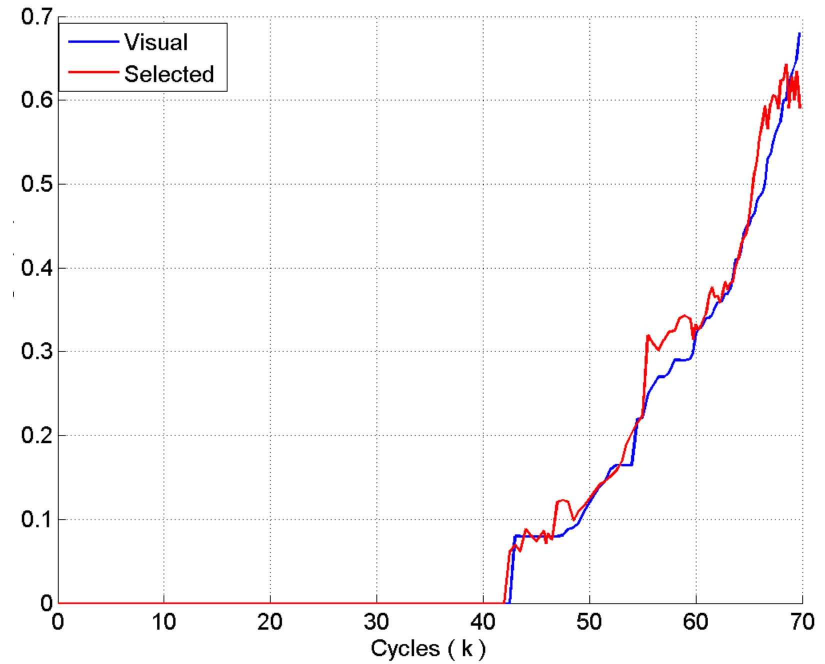
Cycle(n)	*$NN_1(n)$*	*$REG_1(n)$*	*$NN_2(n)$*	*$REG_2(n)$*	*P(n)*
54,000	X	X			
54,500	X	X			X
55,000	X	X			X
55,500	X	X			X
56,000	X	X			X
56,500	X	X			X
57,000	X	X			X
57,500	X	X			X
58,000	X	X			X
58,500	X	X			X
59,000	X	X			X
59,500	X	X			X
59,750	X	X			

Cycle(n)	*$NN_1(n)$*	*$REG_1(n)$*	*$NN_2(n)$*	*$REG_2(n)$*	*P(n)*
41,000					X
41,500					X
42,000			X	X	
42,500	X	X			
43,000	X	X			X
43,500	X	X			
44,000	X	X			X
44,500	X				X
45,000	X	X			X

Selected Crack Lengths vs Cycles

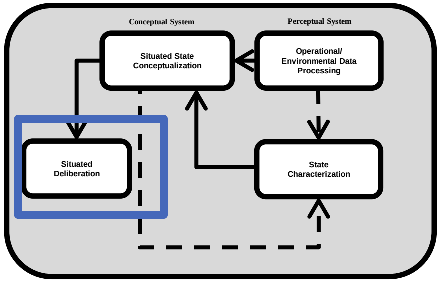
- Application of threshold and fusion rules generate selected crack length at each measurement instant

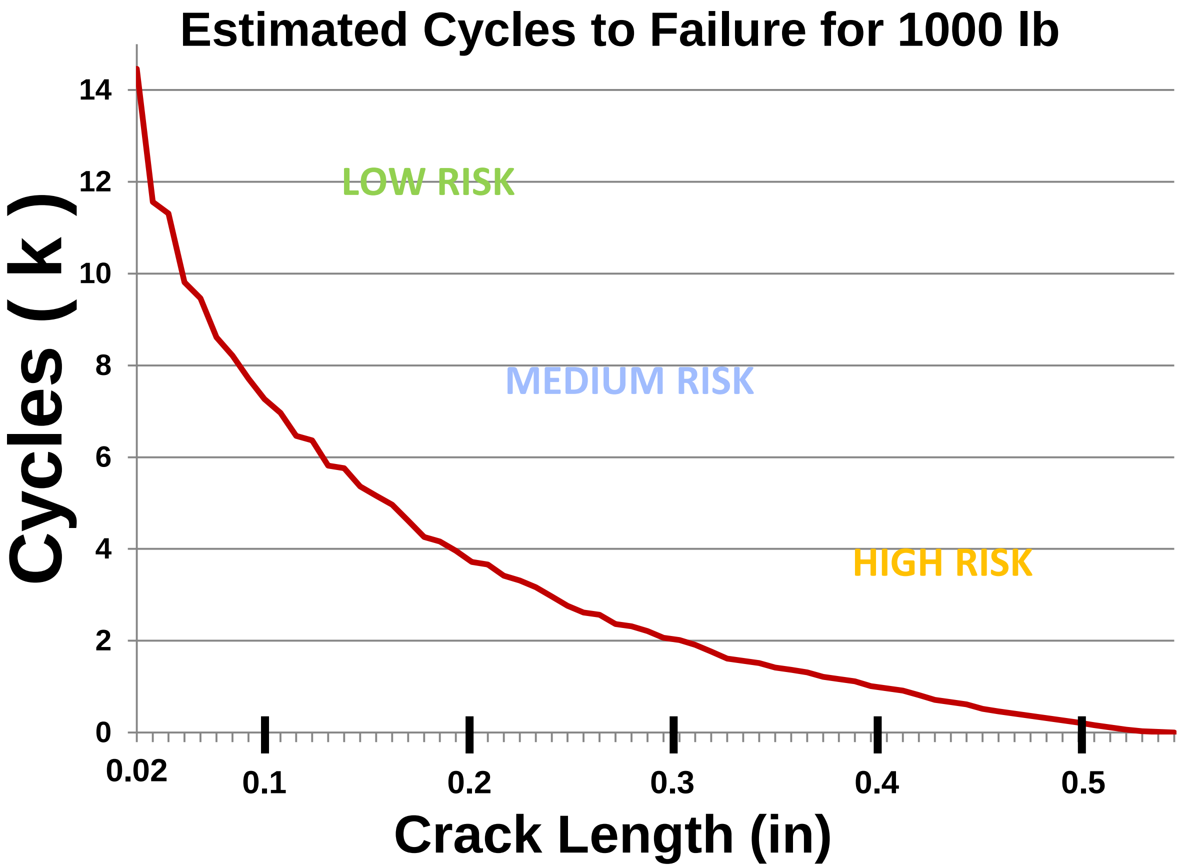




Situated Deliberation

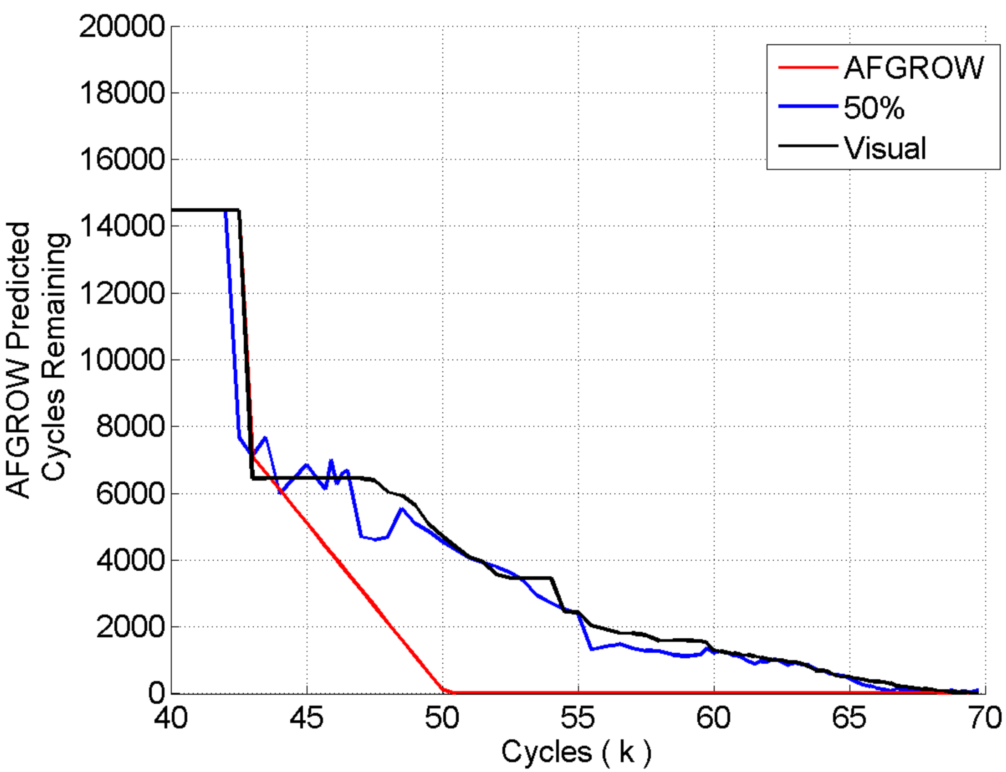
- AFGROW model provides remaining cycles
  - Remaining cycles related to risk of mission failure





Situated Deliberation

- Mission commander receives risk categorized as low, medium, or high based on remaining life at end of mission calculated using mission requirements and current state
  - Example: Assume mission categorized as requiring 4000 cycles at 1000 lb load



Risk Chart for 4K Mission Cycles Requirement at 1000 lb
LOW: > 5K
MEDIUM: 3K – 5K
HIGH: < 3K

Simulation Cycles	AFGROW	50%	Visual
40K			
45K			
47.5K			
50K			

Summary

- An intelligent agent architecture has been demonstrated in a laboratory SHM application
  - The architecture provides a coherent framework for combining perceptual and contextual information, and includes a deliberative processing element to facilitate high level decisions
  - The assumed scenario allows missions to continue even when sensor readings indicate cracks exist
    - A change in CONOPS is needed before the assumed scenario can be a reality.
    - But a new CONOPS can lead to increased availability and lower maintenance costs

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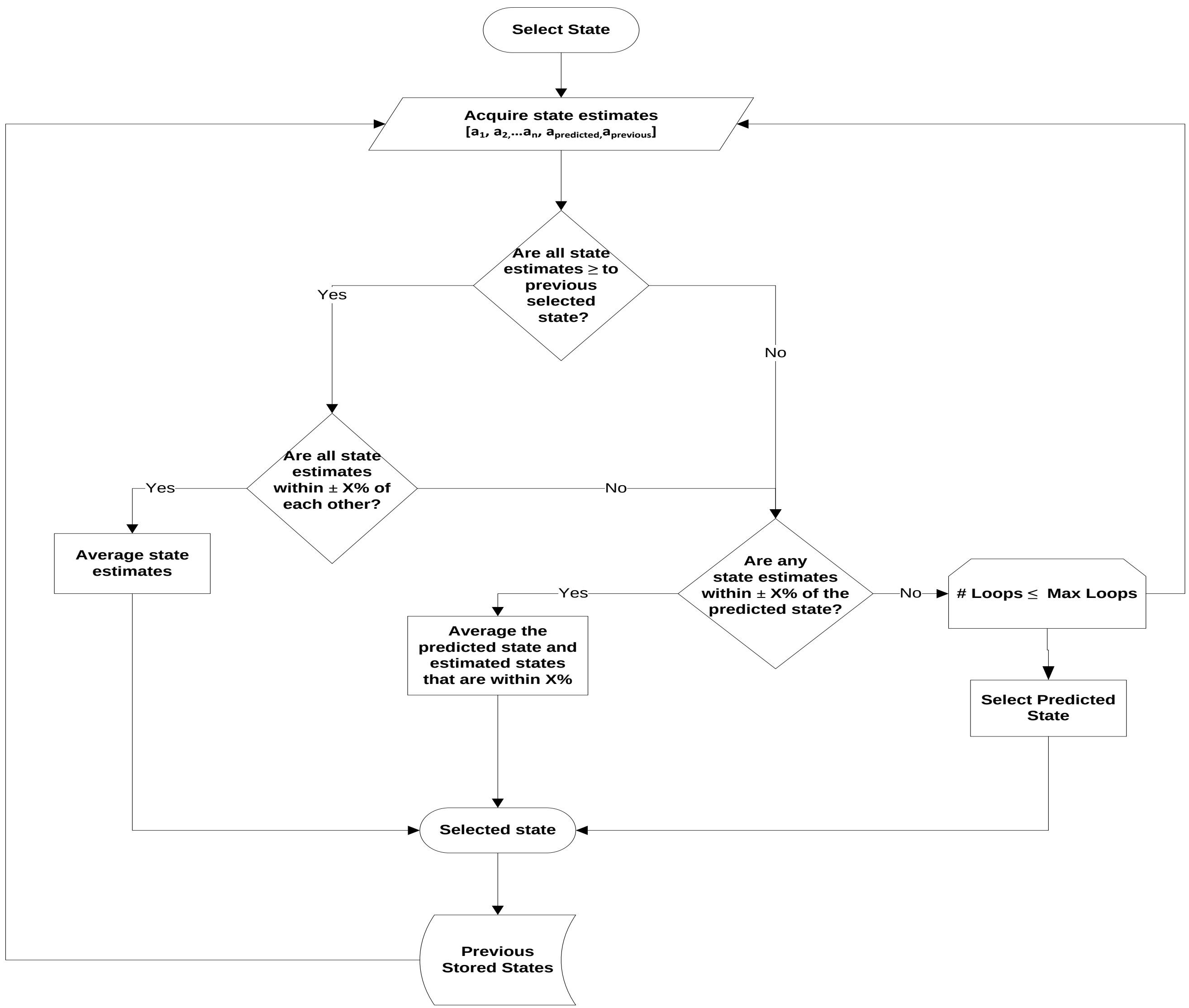
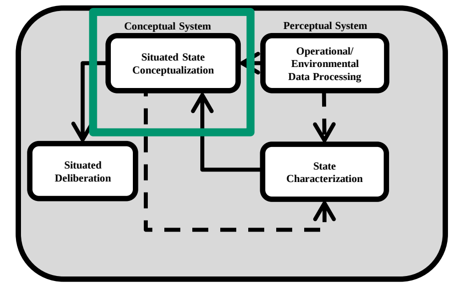
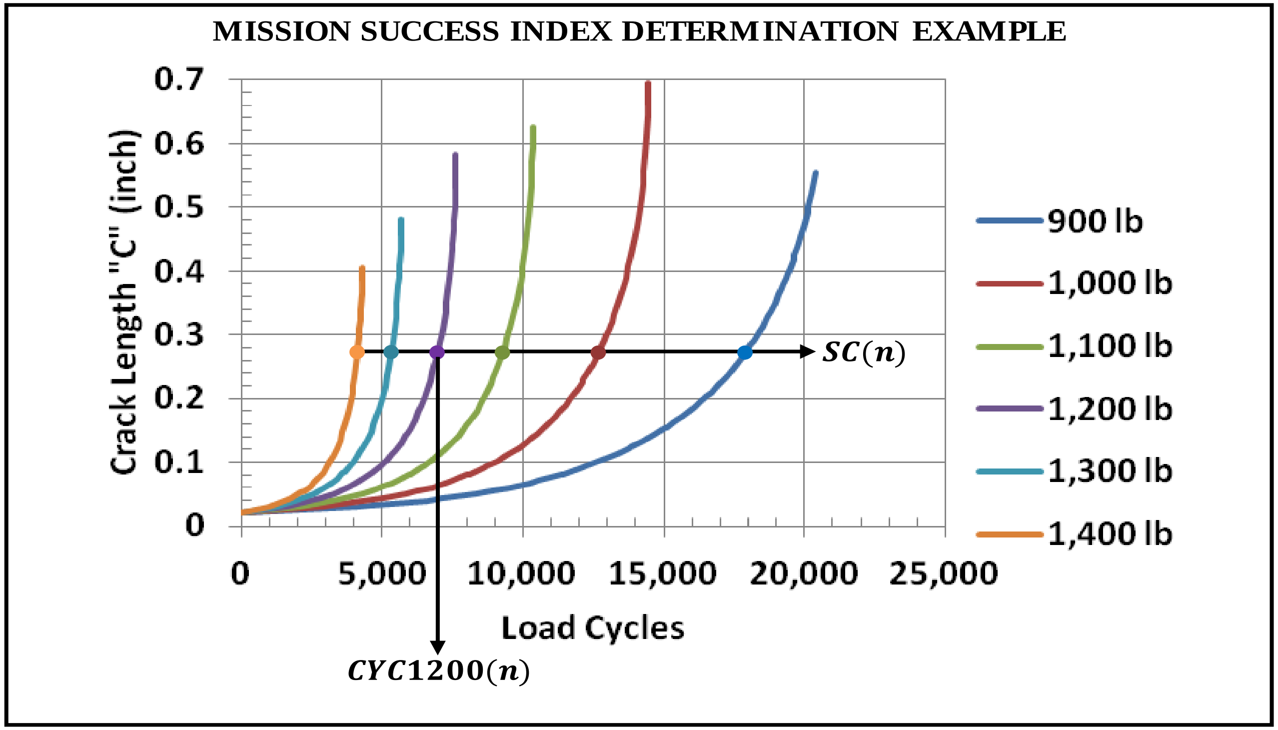
Back Up Slides

Selection Algorithm

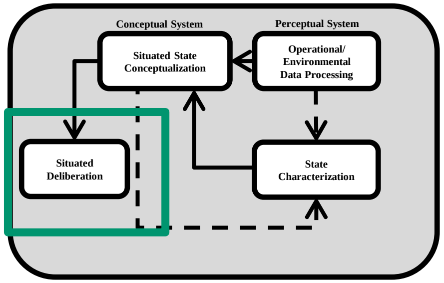




Situated Deliberation



From curves $SC(n) = 0.28$ and $CYC1200(n) = 7000$. The cycle at crack failure for 1200 lb is $MCYC1200 = 7603$. The mission success index is defined as $M_I(n) = \frac{MCYC1200 - CYC1200(n)}{M_C(n)}$ and limited to values from 0 to 1. In this case if an additional 10,000 cycles is required of the aircraft at (n) then the mission success index for a 1200 lb load is $M_I(n) = \frac{7603-7000}{10{,}000} = 0.06$



Selection Algorithm

<u>Crack Selection Decision Algorithm (Decision is biased toward estimation states)</u>

{R is signal percentage index}

If $E_1(n) - R * E_1(n) \leq E_2(n) \leq E_1(n) + R * E_1(n)$ and $E_1(n) - R * E_1(n) \leq E_2(n) \leq E_1(n) + R * E_1(n)$

is true then $SC(n) = \frac{E_1(n)+E_2(n)}{2}$ if false then

If $E_1(n) - R * E_1(n) \leq PC(n) \leq E_1(n) + R * E_1(n)$ and $PC(n) - R * PC(n) \leq E_1(n) \leq PC(n) + R * PC(n)$

is true then $SC(n) = \frac{E_1(n)+PC(n)}{2}$ if false then

If $E_2(n) - R * E_2(n) \leq PC(n) \leq E_2(n) + R * E_2(n)$ and $PC(n) - R * PC(n) \leq E_2(n) \leq PC(n) + R * PC(n)$

is true then $SC(n) = \frac{PC(n)+E_2(n)}{2}$ if false then

{If true result is not returned by this time then considers the other estimates}

If $E_3(n) - R * E_3(n) \leq E_4(n) \leq E_3(n) + R * E_3(n)$ and $E_4(n) - R * E_4(n) \leq E_3(n) \leq E_4(n) + R * E_4(n)$

is true then $SC(n) = \frac{E_3(n)+E_4(n)}{2}$ if false then

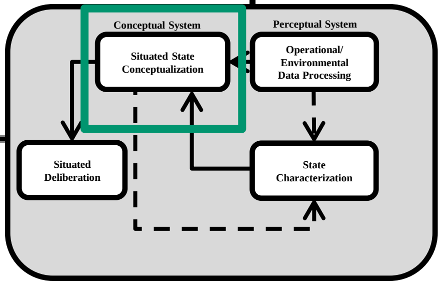
If $E_3(n) - R * E_3(n) \leq PC(n) \leq E_3(n) + R * E_3(n)$ and $PC(n) - R * PC(n) \leq E_3(n) \leq PC(n) + R * PC(n)$

is true then $SC(n) = \frac{E_3(n)+PC(n)}{2}$ if false then

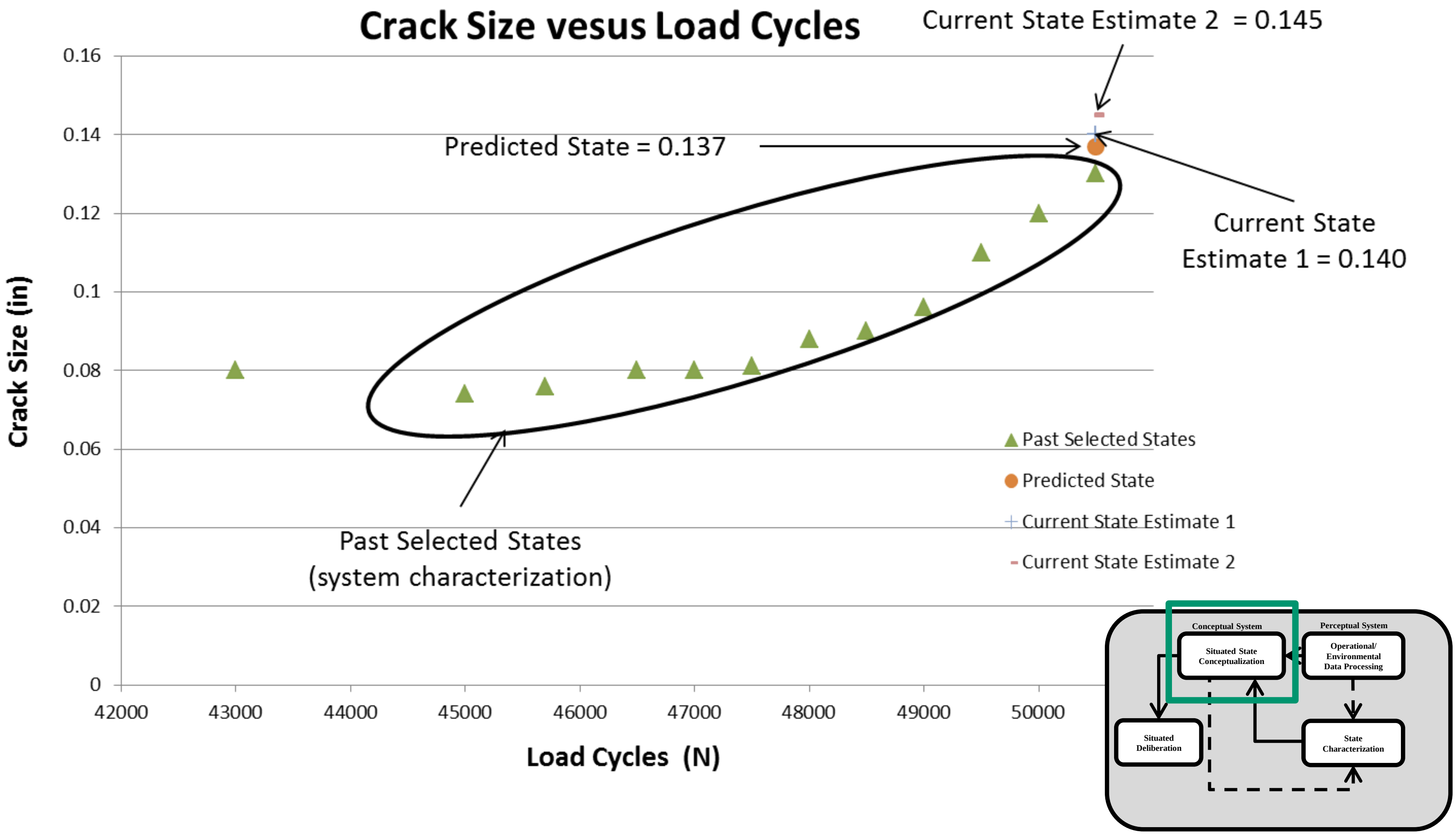
If $E_4(n) - R * E_4(n) \leq PC(n) \leq E_4(n) + R * E_4(n)$ and $PC(n) - R * PC(n) \leq E_4(n) \leq PC(n) + R * PC(n)$

is true then $SC(n) = \frac{PC(n)+E_4(n)}{2}$ if false then

{If true result is not returned by this time then crack is set to crack prediction}



State Selection Example



Current SHM Approaches

- Reflexive system (i.e., agent) suitable for well-defined problems with complete knowledge of environmental and operational conditions the system will encounter during operation (matched training and test conditions, "static database")
- Under the static database conditions, reflexive techniques can correctly characterize states with high confidence.
- Conversely, performance of reflexive systems degrade when presented with data obtained under even slightly different states or operating conditions (i.e., "dynamic database").
- Fragility of current SHM approaches exists primarily because they do not have an intrinsic ability to distinguish between changes in system health states, system operational states, or environmental conditions.

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